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THE 1977 LOW-LEVEL WINDSHEAR WARNING TRIALS AT HEATHROW AIRPORT

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SUMMARY

The results of windshear warning trials at Heathrow Airport carried out in 1977 in conjunction with the collection of pilot reports and flight records are presented and discussed.

The warning service displayed a significant degree of skill in that about 4% of British Airways aircraft using Heathrow reported windshear during warning periods compared to 0.4% in non-warning periods.

The flight records were searched for the maximum airspeed change 'event' (expressed in terms of 'ramp-pair' magnitudes) on each record, and the distribution of these (which approximated to log-normal) used to make estimates of the probability of encountering 'events' of different magnitude. The results were also used to estimate the probability of a pilot 'noticing' an event of given magnitude.

1. INTRODUCTION

The handling problems of large jet transport aircraft in the approach phase due to low level wind variations is now generally referred to colloquially as the 'windshear' problem. Concern with this problem - accentuated by the Kennedy Airport crash in 1975 - led in 1976 to a request from British Airways to the Meteorological Office to investigate the possibility of forecasting conditions likely to produce 'windshear' incidents.

Accordingly in 1977 the Meteorological Office, in cooperation with British Airways and the Royal Air Force, ran low-level windshear warning trials in the two three-month periods January to March (winter trial) and July to September 1977 (summer trial) at Heathrow, Abbotsinch and Elmdon Airports, and at eight RAF airfields. These trials consisted of three parts:

(i) An hourly warning service based on the application of simple meteorological criteria.

(ii) The collection and analysis of written pilot reports of windshear experience, including NIL reports.

(iii) The collection and analysis of flight records from aircraft landing or taking off during periods when warnings were in force.

The principal objectives of these trials were:

a. To use pilot reports to assess the skill of the warning service.

b. To correlate flight records of the incidence of certain types of airspeed change thought most likely to cause handling difficulties (section 3) with pilot reports of windshear and with the warning service.

Since the bulk of aircraft reports of windshear and all flight records analysed originated from Heathrow, the analysis described in this paper is confined to Heathrow for the winter trials only as representing some approach to a homogeneous data set. However, one of us (Durbin 1980) has assessed the skill of warning service in both trials at all airfields, and some reference to this is made in section 2.

2. THE WARNING SERVICE AND PILOT REPORTS

It is now generally realized that a 'windshear' incident may be caused by wind structures which are usually transient in nature, and may or may not contain 'meteorological' shear as a component. The classical situation of an aircraft descending through a quasi-steady vertical shear of the horizontal wind and encountering a 'windshear' incident through the resultant change in airspeed appears to be a relatively rare occurrence.

2.1 Meteorological criteria

These are based on the occurrence of strong mean surface winds, a large vector difference between mean surface wind and gradient wind, strong convective activity, a frontal passage, and nocturnal low level jet. (See Appendix 1a for details). Warnings were also issued if pilot reports of windshear were received.

There is a sense in which 'windshear' incidents associated with strong mean surface winds might be more 'expected' than those associated with thunderstorm squalls, which may interrupt a period of light mean surface winds. This has not, however, been considered a sufficient reason for not issuing warnings in strong mean surface wind conditions.

Every hour throughout the trials, Meteorological Office staff assessed the existing meteorological conditions and incoming pilots' reports of windshear, and if any of the criteria were satisfied, a windshear warning was passed to pilots via the half-hourly Automatic Terminal Information Service (ATIS) broadcast.

2.2 Reporting of Windshear by Pilots

British Airways pilots operating into and out of Heathrow during periods when a warning was in force were asked to complete a standard reporting form (Appendix 1b) whether or not they experienced windshear. Pilots were also asked to complete a form whenever they experienced windshear during periods when no warning was in force. Data logged by the forecasters during the trials were later compiled in machineable form, the details of which are listed in Appendix 1c.

2.3 Results

We require to assess the skill of the forecaster in applying the meteorological critera, and the skill of the warning service in relation to pilot reports of windshear.

2.3.1 The skill of the forecaster

The skill of the forecaster in applying meteorological criteria can be assessed retrospectively by a study of selected meteorological situations to see whether or not warnings should have been issued, not because an aircraft report was received, but whether the meteorological criteria were satisfied. A direct assessment of this type was not made during the 1977 trials, although it appeared from Durbin (1980) that the fraction of total time that warnings were in force at different stations varied from 3% to 12% in the winter trials, and for 1% to 4% in the summer trials, with warnings be issued at civil airfields about twice as often as at RAF airfields. There was also uneveness in the number of warnings issued under different rules. It is unlikely that these differences were entirely climatic in origin, and may reflect the influence of many factors such as inexperience

due to limited periods of trial, and a greater concern with the windshear problem at civil airports than at RAF airports.

It is not profitable to pursue these speculations, but we record here that a direct assessment of forecasting skill was made during some recent trials at Heathrow during the year 18.2.80 - 18.2.81. These trials were restricted to a warning service combined with verbal pilot reports. It was apparent that skill in applying criteria increased during the year. The convective criterion was the most difficult to assess as its application depended upon whether local reports of radar plots were available to the forecaster at Heathrow, but in the end, there was disagreement between the forecaster and assessor in very few cases.

We conclude that, given practice, the forecaster can apply meteorological criteria correctly provided these are simple and relatively few in number.

2.3.2 The skill of the warning service

The basic test of an individual warning is whether or not an aircraft report of shear is received during the period of validity. A two-dimensional contingency table (Table 2) can then be constructed in which each hour during the warning trials is classified as to whether or not a warning was issued, and whether or not an aircraft report was received.

Owing to the essentially transient nature of wind structures (lifetimes of order one minute) liable to cause aircraft handling difficulties, these contingency tables have to be interpreted with some care. The 'success' of a warning will depend upon whether an aircraft happened to encounter a 'windshear' structure passing over the airfield, and if it did, whether the pilot noticed it sufficiently to report it. Thus the probability of 'success' of a warning will increase with the number of aircraft movements occurring during its period of validity. This is apparent from the large variation in the numbers of aircraft reports received from different stations (Durbin 1980) ranging from 140 reports per thousand hours at Heathrow down to 5 per thousand hours at some RAF stations.

In view of this, the main analysis was confined to hourly periods in which ten or more British Airways aircraft used Heathrow. This selection procedure reduced the total sample by about half. The results are summarized in Table 1.

TABLE 1. LOW LEVEL WINDSHEAR WARNING TRIALS:
HEATHROW: JAN-MAR 1977

VARIABLE	NO WARNING ISSUED	WARNING[a] ISSUED UNDER RULE 1-4	5	6	8	E[b]	All	ALL HOURS
1.Total aircraft movements (BE, BESH, BZ)	18298	131	875	490	694	77	2162	20462
2.Total hourly periods	928	7	47	24	36	4	112[c]	1040
3.Hourly periods with at least one aircraft report of shear (% in brackets)	48 (5)	1	19 (40)	8 (33)	17 (47)	1	45 (40)	93
4.Total written aircraft reports	136	6	87	31	57	3	175	311
5.Aircraft reports of shear (any intensity)	71	5	31	15	36	2	84	155
6.Row 5/Row 1(%[d])	0.4	-	3.5	3.1	-	5.2	3.9	0.76

N.B. (a) No warning was issued under rule 7.
(b) E indicates warning issued in error.
(c) This figure is less than total of separate columns as warnings were occasionally issued under more than one rule.
(d) Percentage figures omitted when sample is too small.

TABLE 2. CONTINGENCY TABLES FOR WARNING TRIALS

1977 Winter Trials

R \ W	YES	NO	
YES	45	48	93
NO	67	880	947
	112	928	1040

1980/81 Trials

R \ W	YES	NO	
YES	28	80	108
NO	212	8440	8652
	240	8520	8760

The main features of Tables 1 and 2 are:

(i) 4% of aircraft reported windshear during periods when warnings were in force (8% of total time) compared to 0.4% at other times.

(ii) During the 1977 trials aircraft reports were received during 40% of warning periods and during 5% of non-warning periods. For 1980/81 the corresponding figures were 13% and 1%.

(iii) Warnings were issued most frequently for the convective (Rule 5), frontal (Rule 6) and aircraft report received (Rule 8) criteria. There was no (statistically) significant difference between the 'success' of these three criteria. The strong wind criteria (Rules 1-4) were little used and the nocturnal jet (corresponding to the 'classical' situation of an aircraft descending through a quasi-steady shear) not at all.

Evidence that the Rule 1-4 criteria may have been set too high is provided by Tables 3 and 4 which show clearly that a large number of pilots reports would have been 'caught' by the warning service by relaxing the Rule 1-4 criteria.

(iv) The number of aircraft reports of shear was about the same as the number of NIL reports, whereas (i) above suggests the NIL reports should have far outnumbered the reports of shear. This suggests that requests to return NIL reports have little value - pilots are much less likely to report something that hasn't occurred.

TABLE 3. HOURLY PERIODS* WITH AT LEAST ONE PILOT REPORT OF MODERATE OR SEVERE WINDSHEAR, AS A FUNCTION OF SURFACE WIND SPEED

	SURFACE WIND SPEED						
	0-5	5-10	10-15	15-20	20-25	25 km	ALL
Total hours	148	389	351	130	19	3	1040
(hrs with warnings)	(7)	(16)	(46)	(35)	(7)	(1)	(112)
No.of hours with at least one report of moderate or severe windshear (% of Row1)	0 (0)	2 (0.5)	22 (6.3)	29 (22.3)	8 (42.1)	3 (100)	64 6.2

TABLE 4. HOURLY PERIODS* WITH AT LEAST ONE PILOT REPORT OF MODERATE OR SEVERE WINDSHEAR, AS A FUNCTION OF THE VECTOR DIFFERENCE (MAGNITUDE) BETWEEN SURFACE AND GRADIENT WINDS.

	VECTOR DIFFERENCE						
	0-10	10-20	20-30	30-40	40-50	50 km	ALL
Total hours (hours with warnings)	183 (3)	409 (30)	315 (44)	100 (20)	30 (13)	3 (2)	1040 (112)
No. of hrs with at least one reportof moderate or severe wind-shear (% of Row 1)	0 (0)	9 (2.2)	26 (8.3)	14 (14)	13 (43)	2 (67)	64 6.2

* Only those hourly periods during which at least ten BA aircraft landed or took off are considered.

2.4 Discussion

It appears that the warning service exhibits a significant degree of skill in that the probability of an aircraft report is about an order of magnitude higher during a warning period than during a non-warning period. It may be that the pilot is likely to be more 'sensitive' to windshear when a warning is in force, and this may bias this result. Psychological factors such as these cannot be quantified, but are unlikely to account for the entire difference between warning and non-warning periods.

In addition, Table 2 shows another way of assessing the results in a less favourable light. In the 1977 trials the warning service 'caught' only about half and in the 1980/81 trials only about one-quarter of the total reports. (The difference between these two trials may be mainly accounted for by the aircraft movement requirement applied to the 1977 trials, but not to the 1980/81 trials).

This result demonstrates that there is a trade-off between catching more events by relaxing the meteorological criteria and the risk of undue 'overwarning'.

Whatever procedure is adopted, the overriding fact is that most aircraft landing or taking-off do not encounter windshear, whether a warning is in force or not. Thus a warning service can never do more than alert the pilot to an increased probability (unlikely to exceed 10%) of encountering windshear. The 'success' of a warning service judged solely in terms of the fraction of aircraft

reports 'caught' is likely to be better at busy airports, but is a misleading measure of success for the reasons already discussed.

3. THE FLIGHT RECORDER DATA

For the period of the 1977 Low-Level Windshear Warning Trials, an arrangement was made with British Airways (BA) to receive aircraft-recorded flight data for the approach and climb-out phases for their own Heathrow flights during periods when windshear warnings were in force. The large majority of data received under this arrangement was from Trident aircraft for which IGS (Inertial Ground Speed) values were not available. Analysis of the flight-recorder data has been concentrated on Trident records.

3.1 Quality control and filtering of the data

In total, including all types of BA aircraft, magnetic tape information was available for about 1000 take-off and landings, but the number of tapes for which useful data could be derived was substantially less, due to:-

(i) Unacceptably high rate of corrupt data, or inability to read tapes.

(ii) Inability to determine sufficiently accurately datum values for relevant variables, particularly longitudinal acceleration (g_x) and normal acceleration (g_z), important terms in the estimation of the rate of change of ground speed $\left(\frac{\partial V_g}{\partial t}\right)$. Any flights for which a reasonable datum values could not be obtained were not used in the subsequent analysis. Following preliminary elimination of flights for these reasons, 239 winter and 56 summer flights remained.

The quality control procedures applied to the data and the methods of filtering the variables required (for analysis of changes in headwind component) are described in Appendix 2. After quality control and filtering, the following variables were available for each flight, at the rate of 1 Hz:-

Computed airspeed	(V_a	- knots)
Pressure altitude	(z_p	- feet)
Longitudinal acceleration	(g_x	- g-units)
Pitch	(θ	- degrees)
Roll	(ϕ	- degrees)
Normal acceleration	(g_z	- g-units)

g_x and g_z relate to axes fixed in the aircraft.

The first two (V_a, z_p), originally recorded at 1 Hz remain unfiltered; g_x (originally at 2 Hz), θ (4 Hz), ϕ (4 Hz) and g_z (8 Hz) were all filtered over 1-second periods, using binomial or triangular filters, to produce smoothed values at 1-second intervals. Only that portion of each flight covering the lowest 2500 feet was included.

From the filtered values, changes in ground speed (ΔV_g) over 1-second intervals are estimated as follows:-

$$\Delta V_g \approx 19.06 (g_x \cos\theta - g_z \sin\theta \cos\phi) \quad (1)$$

If ΔV_a is the change in airspeed over corresponding 1 second intervals, then the change in headwind component (ΔU) is approximately $\Delta V_a - \Delta V_g$

3.2 Application of windshear analysis programme to flight data

The analysis of flight records was based on advice and programmes from RAE Bedford. They find (Haynes 1980) that an airspeed change followed by another airspeed change of opposite sign on a time-scale tuned in some sense to the handling/control response time (several seconds) characteristic of large jet transport aircraft may be the basic wind structure most likely to be experienced as 'windshear'.

This pair of airspeed changes is referred to as a 'ramp pair' and is more akin to a 'rate of shear' along the aircraft track, and does not correspond to the meteorological definition of windshear as a change in windspeed normal to the mean wind direction.

The basic 'ramp pair' pattern is illustrated in Fig. 2, while the simple 'ramp' is illustrated in Fig. 1.

A Windshear Analysis Program based on an early version of that developed by Haynes (1980) was applied to the filtered (quality controlled) Trident records. The program requires as input a series of headwind component values at 1 Hz; this series U(t) is initially smoothed (low-pass filter) to form the smoothed headwind component UI(t)

$$UI(t) = \frac{1}{4}[U(t-\Delta t) + 2U(t) + U(t+\Delta t)] \quad (2)$$

(where Δt = 1 second). The smoothed headwind component is then differenced over time T, this differencing effectively acting as a high pass filter in removing the low frequency content in U(t). RAE's current version of the program then computes the generalised difference function UID, defined as:-

$$UID(\tilde{t}) = \frac{1}{NR}\left\{[UI(t+T) - UI(t)] - (NR-1)[UI(t+2T+T_3) - UI(t+T+T_3)]\right\} \quad (3)$$

where $\tilde{t} = (t + \frac{T}{2}) + (NR-1)(\frac{T+T_3}{2})$

so that the position in time of the generalised difference function relates to the centre of the portion of the velocity profile from which it was computed.

Values of T (usually 4, 8 and 16 seconds) and T_s (0, T/2 and T) are chosen to represent different ramp-pair shapes (Fig. 2). NR is a parameter which takes values 1 (single ramp) or 2 (ramp pair). For NR = 1.

$$UID(\tilde{t}) = [UI(t+T) - UI(t)] \qquad (4)$$

where $\tilde{t} = t + \frac{T}{2}$

This term is then simply a measure of the velocity gradient over T seconds (Fig. 1). For NR = 2

$$UID(\tilde{t}) = \tfrac{1}{2}\{[UI(t+T) - UI(t)] - [UI(t+2T+T_s) - UI(t+T+T_s)]\} \qquad (5)$$

where $\tilde{t} = (t + \frac{T}{2}) + (\frac{T+T_s}{2}) = t + T + \frac{T_s}{2}$

This is a measure of the change in velocity gradient over the time period 2T + Ts, centred on time $\tilde{t}$ (Fig. 2).

A large peak in a filter output is the result of a large gradient in the velocity component (NR = 1) or a large change in gradient (NR = 2), and it is these peaks which form the basis of the method of analysis of aircraft recorded wind information advocated by RAE Bedford.

In practice, the response time of an aircraft to wind variations depends on its dynamic characteristics. The variable parameter T is incorporated in order to make the method independent of aircraft size type; it is defined as the time interval over which the gradient of headwind component is computed. The parameter T_s represents the time interval separating the end of one headwind component gradient from the start of the next (see Figs 1, 2). In the current version of RAE's program, values of T and T_s are chosen to cover the range appropriate to the assessment of windshear hazards to transport aircraft. Our analysis of BA Trident data has concentrated on ramp-pairs (NR = 2) only and used T = 4 and 8 seconds and T_s = 0, T/2 and T.

As our headwinds were based on recorded values of g_x, g_z, θ and (less importantly) ϕ, small inaccuracies in these variables (particularly g_x) lead to spurious rates of changes of ground speed and thus contaminate rates of change (or gradients) of derived headwind component. The derived changes in the gradients of headwind component are, on the other hand, unaffected provided that the spurious rates of change of groundspeed are approximately constant throughout the period of an approach or landing, as in general they appeared to be.

We are concerned with the rate of change of UID, and have used an alternative variable UID_T which is the same as that used by RAE in the early stages of the development of the Windshear Analysis Program; this is

$$UID_T(t) = \frac{1}{T}\left\{\left[UI(t+2\tau+T_s) - UI(t+T+T_s)\right] - \left[UI(t+T) - UI(t)\right]\right\} \qquad (6)$$

so that

$$UID_T = \frac{2}{T} \text{ UID expressed in units of kn } s^{-1} \text{ in this paper.}$$

A decrease of headwind over time T followed by an increase over T implies positive UID_T, and vice versa. Note also that Haynes (1980) defines an alternative UID_T = UID/T as a measure of change of shear.

Our version of this Windshear Analysis Program was applied to the quality control BA Trident records to produce for each landing or take-off, a Flight Summary in the format shown in Appendix 3. The data created includes details of the maximum and minimum values of the quality UID encountered in the lowest 1000 feet of the approach or climb-out, for the 6 combinations of T and T_s chosen. These combinations are referred to as 404 (TT_sT), 424, 444, 808, 848, 888 ramp pairs. The relevant hourly data used in the analysis of pilots' reports of Windshear has been included in each Flight Summary. This data also includes the meteorological data logged by forecasters at Heathrow during the Low-level Windshear Warning Trials in 1977 and its content is listed in full in Appendix 1c. These records contained in the Flight Summary data set have been used as the basis for the discussion of the results.

3.3 Results

Some details of flight records containing ramp pairs exceeding 3.5 knots s^{-1} are listed in Table 5. The distribution of the largest ramp pairs, μ (= $|UID_T|_{max}$), observed on each of the 239 winter flights are related to the incidence of pilot reports and windshear warnings.

TABLE 5. SUMMARY OF FLIGHTS (HEATHROW WINTER TRIALS) for which $|UID_T|_{max} \geq 3.5$ kn s^{-1}

Date	GMT	Landing or T/off	Runway	$(UID_T)_{max}$	$(UID_T)_{min}$	Surface Wind	Gradient Wind	Warning Status
25.1.77	1426	L	28	2.8	-3.9	210/15	230/50	8
25.1.77	1504	L	23	3.9	-3.7	210/16	230/50	8
25.1.77	1910	L	23	4.1	-5.0	210/26	230/70	8
25.1.77	1941	T/O	23	3.8	-3.2	210/26	230/70	8
25.1.77	1955	L	23	5.4	-3.9	210/26	230/70	8
5.2.77	2022	T/O	28	4.3	-5.5	180/13	230/35	E
7.2.77	0458	L	28	2.4	-3.5	220/16	260/42	6
7.2.77	0833	T/O	28	2.7	-4.1	220/10	250/30	8
7.2.77	1613	T/O	28	3.6	-3.0	230/15	260/52	5
7.2.77	1640	T/O	28	2.7	-4.0	230/15	260/52	5
7.2.77	1648	L	28	4.6	-4.8	230/15	260/52	5
18.2.77	0212	T/O	28	4.1	-2.6	200/13	250/38	0
18.2.77	2123	L	23	3.6	-4.5	220/20	250/60	8
18.2.77	2209	L	28	5.0	-4.8	240/24	250/60	8
21.2.77	1544	L	28	4.0	-3.7	200/13	240/29	0
4.3.77	1104	L	28	3.6	-3.1	290/17	320/40	8
8.3.77	1514	L	23	3.1	-3.6	180/15	210/34	0
10.3.77	1852	L	23	4.9	-3.6	180/13	210/40	0
15.3.77	1707	L	23	4.1	-5.0	170/16	210/52	8
15.3.77	1910	L	23	5.2	-4.1	170/19	200/55	0
15.3.77	2019	T/O	23	3.8	-3.4	170/18	210/46	0
15.3.77	2103	L	23	3.1	-4.2	170/19	220/40	0
17.3.77	1108	L	23	3.5	-3.9	200/18	230/40	5
18.3.77	1432	L	28	3.5	-3.2	200/13	230/30	5
28.3.77	0931	T/O	28	3.9	-4.1	350/18	020/35	0
28.3.77	1023	T/O	10	3.1	-4.0	350/19	020/35	8
28.3.77	1255	T/O	10	3.5	-3.1	360/23	020/33	0

Notes: $(UID_T)_{max}$, $(UID_T)_{min}$ relate to 404-type ramp pairs over lowest 2000 feet. SURFACE and GRADIENT WIND relate to previous clock hour. Units are degrees/knots. If WARNING STATUS = 0 no Windshear Warning was in force; if non-zero the value indicate the rule number under which a warning was issued. (E) indicates that a warning was issued in error).

3.3.1. Relationship to pilot reports

Frequency distributions of μ for each of the six ramp-pair types defined in Section 3.2 are shown in Fig. 3 for the winter flights. Each histogram column is divided into two sections depending upon whether (shaded) or not (unshaded) a pilot report was received in the same clock hour on the flight record. The two distribitions obtained in this way for each ramp pair type were shown (using Student's t-test) to be different with a high level of significance for all ramp pair types. Although the main values of the shaded and unshaded distributions only differ by about 10%, the main differences lie in the distribution tails - flight records with high values of μ occur more frequently in 'pilot report' hours than in no report hours; the reverse is also true.

TABLE 6. SUMMARY OF STATISTICS OF μ (kn s^{-1})

Ramp-pair type	R	N	R	N
404	2.179	1.861	1.025	1.009
424	2.075	1.749	0.955	0.950
444	2.047	1.655	0.881	0.837
808	1.022	0.813	0.456	0.395
848	1.020	0.809	0.505	0.405
888	1.046	0.845	0.529	0.424

R - hours in which report of at least slight windshear was received (86 flight records).

N - hours in which no pilot report was received (153 flight records).

The characteristics of the histograms appear insensitive to ramp-pair type - the factor of 2 shift between the '4' series and the '8' series appears to be accounted for almost entirely by the factor of 2 change in T.

The distributions shown in Fig. 3 may be used to give some indication of:

a. the probability of an aircraft encountering a ramp-pair magnitude exceeding any given threshold in a period where other aircraft are reporting windshear encounters.

b. the probability of a pilot 'noticing' a given value of μ.

a. Inspection of the histograms suggest a resemblance to a log-normal distribution. Accordingly the R flight records from the '4' and '8' type distributions were combined to form two populations and used to plot μ against cumulative percentage on log-probability co-ordinates as in Fig. 4.

Linear regression lines are drawn and show a very close fit to the observations. This suggests that some degree of linear extrapolation may be justified, and leads to the estimate that a '4' type value of of 10 kn s^{-1} (or an '8' type value of 5 kn s^{-1}) will be exceeded on about 1 in 10^4 landings or take-offs in hours when pilots are reporting windshear, while 17 kn s^{-1} (8.5) is exceeded on about 1 in 10^6 landings, although extrapolation to this degree may not be justified. Since aircraft reports were received in only about 10% of total hours during the warning trials at Heathrow, these probabilities could be an order of magnitude less for landings/take-offs at any time.* In physical terms a value of μ of 10 kn s^{-1} would be produced by an airspeed change of x knots followed by another change of x $\pm$ 40 kn over a total period of 8 s (404-type) to 24 s (888-type).

b. Fig. 3 does not relate the number of pilot reports to the rate of aircraft movements. When these are taken into account, a quantity $P_R(\mu)$ can be extracted

$$P_R(\mu) = (\Sigma R/\Sigma M)_\mu \qquad (7)$$

where R is the number of pilot reports of shear received and M the number of aircraft movements during a given clock hour in which a flight record was displaying a given value of μ. Σ represents the summation over all flight records reporting maximum ramp-pair magnitudes in the interval $\mu \pm \frac{\delta\mu}{2}$, where $\delta\mu$ is large enough to include a statistically large sample. In the cases where more than one flight record (yielding different values of μ) are obtained in a given clock hour, the values of R and M for that hour are divided by the number of flight records received in that hour in order to avoid counting the same reports and movements more than once. $P_R(\mu)$ thus defined is a measure of the probability that a pilot will 'notice' a ramp-pair of magnitude μ.

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* This will not agree with an estimate of probabilities obtained from the histograms corresponding to non-reporting hours, since this sample is heavily biassed to the requirement that flight records were obtained only when warnings were in force.

Values of P_R obtained for the 404 and 808 classes are shown in Table 7. Linear regression of P_R with its corresponding mid-class values of μ yields correlation coefficients which are significant at the 3% level for the 404 and the 1% level for the 808 classes. The levels of probability are quite low, only exceeding 5% for the largest values of μ. This is not surprising since the 239 landings and take-offs occupy only about 0.5% of total time, so that the probability of the sample containing a large event that all pilots would 'notice' and some might report is very small.

3.3.2 Relationship to the warning service

162 out of the total sample of 239 flight records analysed were obtained during warning periods, and 55 of the remainder were obtained on a day on which a warning was issued. An analysis of the distribution of values of μ was made for 'warning' and 'non-warning' periods in the same way as for 'pilot report' and 'no pilot report' hours in section 3.3.1. The difference between the 'warning and non-warning' population was not statistically significant. This may seem surprising in view of the large differences in the relative frequency of pilot reports received in 'warning' and 'non-warning' hours, but may be accounted for by the heavily biassed choice of flight records. In addition, 60 of the flight records were common to both the 'warning' and 'pilot report' samples. This is reflected by the similarity of the cumulative percentage probability plots in the two halves of Fig. 4.

The flight records can also be used in principle to check a main result of the warning service that the probability (P_w) of an aircraft reporting a windshear incident during a warning hour (Table 1) is 3.9%. P_w can also be derived from

$$P_W = \int_0^{\infty} P_R \, p_\mu \, d\mu \qquad (8)$$

where p_μ is the probability that a maximum ramp-pair magnitude will lie between μ and $\mu + d\mu$. (Note that p_μ is a probability density, while P_R is a probability).

Eq. 8 was evaluated for the 404 and 808 ramp-pair types (details in Table 7) and a value of P_w of 3.2% obtained for both ramp-pair types. These samples were then divided into 'warning' and 'non-warning' categories, and Eq. 8 evaluated for each sample with the result shown in Table 8.

TABLE 7: VALUES OF P_R, P_W, $p_\mu \delta\mu$.

404 type			808 type		
μ-interval (km s^{-1})	P_R (%)	$p_\mu \delta\mu$ (%)	μ-interval (km s^{-1})	P_R (%)	$p_\mu \delta\mu$ (%)
0 - 1	0.5	13.5	0 - 0.5	1.0	14.8
1 - 1.5	4.2	18.3	0.5 - 0.75	3.6	23.9
1.5 - 2.2	3.4	18.7	0.75 - 1	3.5	24.6
2 - 2.5	2.3	21.4	1 - 1.25	3.1	15.1
2.5 - 3	3.3	13.4	1.25 - 1.5	4.4	9.1
3 - 4	5.8	11.7	1.5 - 2	3.7	11.0
4 - 5	5.1	2.5	2 - 3	6.5	1.5
5 - 6	5.4	0.1			
$P_W = \sum P_R p_\mu \delta\mu$ =		3.2%	$\sum P_R p_\mu \delta\mu$ =		3.2%
a_0 =	1.5		a_0 =	1.3	
a_1 =	0.82		a_1 =	1.9	
r =	0.78		r =	0.88	
P =	3%		P =	1%	

a_0, a_1 are coefficients in regression equation $P_R = a_1 \quad + a_0$ (%)

r is correlation coefficient and P its level of significance.

TABLE 8: VALUES OF P_W (%) FOR WARNING (W) AND NON-WARNING (N) PERIODS.

	404-type	808-type
W	3.5	3.6
N	2.6	2.7

The values of P_W obtained for the warning periods thus agree well with the value of 3.9% quoted in Table 1, but the values of P_W for the non-warning periods are a factor of 6 to 7 higher than that (0.4%) given in Table 1. This is not surprising in view of the biassed selection of flight records. There is little reasonable doubt that flight records obtained at random would yield much lower values of P_W.

ACKNOWLEDGEMENTS

Our thanks are due to the meteorological staff at the civil and RAF airports for operating the warning service; to the British Airways and RAF aircrews who provided the reports of windshear; to the Flight Data Recording section of British Airways for providing the flight record data with the necessary information to enable us to create a flight record data set, and to the Flight Systems Division of the Royal Aircraft Establishment, Bedford for the provision of advice and programme details relating to the analysis of the flight record data set.

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FIGURE LEGENDS

Fig. 1. Idealized headwind component profile for single ramp.

Fig. 2. Idealized headwind component profile for ramp-pair.

Fig. 3. Histograms of maximum ramp-pair magnitudes (either sign), , for 239 flight records for the ramp-pair types indicated. Unshaded sections correspond to clock hours when no pilot reports were received; shaded areas to clock hours when one or more pilot reports were received.

Fig. 4. Cumulative frequency representation of μ-distribution for hours in which pilot reports were received (lower two curves) and for hours in which warnings were issued (upper two curves). The 404, 424, 444 populations have been combined ('4'-type) for this purpose, and similarly for the '8'-type.

The legends to Appendix Figures A1-A5 are on the figures, or described in the text.

APPENDIX 1. WINDSHEAR WARNING SERVICE

a. Meteorological Criteria

Notation: $\underset{\sim}{V}_{10}$ = Surface (10-metre) wind (vector)

$V_{10} = |\underset{\sim}{V}_{10}|$ = Surface wind speed (scalar)

$\underset{\sim}{V}_G$ = Gradient (600m or 2000 ft) wind (vector)

$V_G = |\underset{\sim}{V}_G|$ = Gradient wind speed (scalar)

(i) Winter Trial

A warning should be issued if any of the following criteria are satisfied:-

(1) $V_{10} \geq 30$ kt

(2) $V_{10} \geq 10$ kt and $V_G - 2V_{10} \geq 25$ kt

(3) $V_{10} < 10$ kt and $|\underset{\sim}{V}_G - \underset{\sim}{V}_{10}| \geq 40$ kt

(4) $V_{10} < 10$ kt and $|\underset{\sim}{V}_G - \underset{\sim}{V}_{10}| \geq 30$ kt,

and an isothermal or inversion layer is present below 600 m

(5) THUNDERSTORM(S) within 20 km and/or CUMULONIMBUS within 10 km of the approach/climbout.

(6) FRONTAL ZONE below 600 m on the approach/climbout, with

(a) vector wind change across it of at least 10 kt magnitude (noted either locally or at a neighbouring station during passage of the front)

or (b) temperature difference across it of at least 5 degrees C

or (c) speed of at least 30 kt.

(7) Significant LOW-LEVEL JET suspected below 600m (separate rules at Appendix 1C)

(8) AIRCRAFT REPORT(S) of low-level wind shear received during the previous hour.

(ii) Summer Trial

A warning should be issued if any of the following criteria are satisfied:

(1) $V_{10} \geq 30$ kt

(2) Winter trial criterion not used in Summer trial

(3) $|\underset{\sim}{V}_G - \underset{\sim}{V}_{10}| \geq 40$ kt

(4) $|\underset{\sim}{V}_G - \underset{\sim}{V}_{10}| \geq 30$ kt and an inversion or isothermal layer is present below 600 m

(5) there are

(a) THUNDERSTORM(S) within 10 km
(b) CUMULONIMBUS cloud(s) within 5 km

} having a component of motion towards the station

(6) there is, on the approach/climbout a FRONTAL SURFACE or other DISCONTINUITY below 600 m with

(a) vector wind change across it of at least 10 kt magnitude - noted either locally or from its passage through a nearby station

or (b) temperature difference across it of at least 5 degrees C

or (c) speed of at least 30 kt

(7) a significant LOW-LEVEL JET is suspected at or below 600 m (Criteria for this are unchanged from the first trial)

(8) AIRCRAFT REPORT of significant low-level wind shear received during the previous hour

Notes

(i) The form of a warning issued under Rules 1-7 is to be:
'Wind Shear expected below 2,000 ft'

(ii) The form of a warning issued under Rule 8 is to be:
'Wind Shear reported and expected below 2,000 ft'.

(iii) Low Level Jet Criteria

Criteria to be tested at observation times 2100, 0000, 0300 and 0600 GMT.

A low level (nocturnal) jet should be suspected if all the following criteria are satisfied:-

(1) Time is in the range (sunset+3 hrs) to (sunrise+1 hr).

(2) A ground-based inversion or isothermal layer is present, and has been present for at least the preceding three observations, and

$$T_aT_a(\max) - T_aT_a \geq 10\ C$$

(3) $V_{10} < 10$ kt and $V_{10}(\max) \geq 10$ kt.

(4) $V_G \geq 10$ kt and V_G (sunset) ≥ 10 kt.

(5) No surface front has passed through since 1200 GMT.

Notes (i) $V_{10}(\max)$ and $T_aT_a(\max)$ are the maximum reported values of V_{10} and T_aT_a from 1300 to 1800 GMT inclusive (previous afternoon).

(ii) If all the criteria are satisfied, then a low level jet should be suspected for the current hour and the succeeding two hours, and the warnings will be issued throughout the three-hour period.

c. Description of data-set containing meteorological observations, aircraft movement statistics and statistics of pilots' (written) reports of Windshear. (One record per hour).

Item No.	Symbol	Description	(Inits/Studies)
1	iii	Station number (= 772 for Heathrow)	
2	mmddgg	Month/day/GMT	
3	dd	Surface wind direction } $\underset{\sim}{V}_{10}$	(tens of degrees true)
4	ff	Surface wind speed } $\underset{\sim}{V}_{10}$	(whole knots)
5	$f_g f_g$	Maximum gust in last hour	(whole knots
6	$T_a T_a$	Surface dry-bulb temperature	(whole degrees C)
7	$d_G d_G$	Gradient wind direction } $\underset{\sim}{V}_G$	(tens of degrees true)
8	$f_G f_G$	Gradient wind speed } $\underset{\sim}{V}_G$	(whole knots)
9	$f_a f_a$	$\lvert\underset{\sim}{V}_G\rvert - 2\lvert\underset{\sim}{V}_{10}\rvert$	(whole knots)
10	$d_b d_b$	Direction of shear $\underset{\sim}{V}_G - \underset{\sim}{V}_{10}$	(tens of degrees true)
11	$f_b f_b$	Magnitude of shear $\lvert\underset{\sim}{V}_G - \underset{\sim}{V}_{10}\rvert$	(whole knots)
12	I	Inversion in lowest 600 m ?	(Ø ≡ NO, 1 ≡ YES)
13 *	$T_i T_i$	Magnitude of inversion, if present	(whole degrees C)
14	T	Thunderstorm within 10 km[(b)] ?	(Ø = NO, 1 = YES)
15	C	Cumulonimbus within 5 km [(c)] ?	(Ø = NO, 1 = YES)
16 *	M	Cumulonimbus has component of motion towards station ?	(Ø = NO, 1 = YES)
17	S	Type of front or other discontinuity, if present	(S-code)
18	$f_c f_c$	Surface wind change across the front/ discontinuity	(whole knots)
19	$f_s f_s$	Speed of front/discontinuity	(whole knots)
20	$T_c T_c$	Surface temperature change across front/discontinuity	(whole degrees C)
21	J	Low level jet suspected	(Ø = NO, 1 = YES)
22	W	Wind shear warning issued	(W-code)
23	(spare)		
24	R_1	Rule under which a warning should have been issued	(Rules 1-7)
25	R_2	Rule under which a warning was issued	(Rules 1-9)
26	R_3	As R_2, except when R_2 = 8 (gives appropriate met. rule)	(Rules 1-7, 9)
27	(spare)		
28	(spare)		

29	M_{gg}	BA aircraft movements during hour gg to gg+1	
30	n_0	No. of aircraft reporting NIL Windshear	)
31	n_1	No. of aircraft reporting SLIGHT Windshear	)
32	n_2	No. of aircraft reporting MODERATE Windshear	) during hour gg to gg+1
33	n_3	No. of aircraft reporting SEVERE Windshear	)
34	n_4	No. of aircraft reporting SLT,MOD or SEV Windshear	)
35	r	Predominant runway in use	(r-code)
36-40	(spare)		

* Not included for Winter Trial. Other differences in Winter Trial - (a) 10-min, (b) 20 km, (c) 10 km.

Appendix 2 - Quality Control and filtering of Flight Records

Figure A1 shows an example of a typical time series of the six variables listed in section 3.1 during the first 25 seconds of a take-off (2022 GMT 5 February 1977). A computer program was developed to quality control these variables, and to create new data-sets for each flight, in which:-

(i) isolated corrupt values or short sequences of corrupt values are replaced by acceptable values.

(ii) the recording rate of each variable written (to the new data-set) is reduced to a common rate of 1Hz; variables recorded at, or more frequently than, 2 Hz (g_x, , $\emptyset$, g_z) were filtered over one-second periods, using simple triangular or binomial filters, as illustrated in Figure A2. The different filters were chosen to achieve similar matching of the filtering function amplitude for periodicities in excess of 2 seconds.

(iii) Only that portion of each take-off or landing covering the lowest 2500 feet was included.

The main function of this stage of the quality control was to:-

(i) check that the values of the six main variables lay within acceptable limits; these limits are VMIN and VMAX in Table A1 below.

(ii) check that the differences between any single value and its immediate neighbours in the time series did not exceed prescribed limits; these limits are VDIFF in Table A1.

TABLE A1. QUALITY CONTROL CRITERIA

VARIABLE	UNIT	VMIN	VMAX	VDIFF
CAS	knots	100	400	30
Z_p	feet	-100	2500	100
g_x	g-units	-0.5	+0.5	0.3
θ	degrees	- 30	+ 30	3.0
$\emptyset$	degrees	- 45	+ 45	5.0
g_z	g-units	-1.0	+4.0	1.0

If any value lay outside the prescribed range VMIN to VMAX, it was automatically replaced by its predecessor in the time series (prior to filtering), provided that value lay within the prescribed limits. If the VDIFF criteria was exceeded

for both neighbouring values (prior to filtering), the offending value was replaced by the arithmetic average of its two neighbours. An "error score", a measure of the proportion of data points, within any one second period, with values failing a quality control test, was computed for each variable for each one second period; an error score of zero associated with a filtered value implied that all the values covered by the filter satisfied the quality control criteria, while an error score of 16 implied that all the values covered by the filter had failed the criteria, and had to be replaced by acceptable values. The error scores were written to the new quality controlled and filtered data-set. A sample of the information contained within the fresh data-set is shown in Figure A3. It includes date/time information (1048 GMT, 13 January 1977 in this example) heading (degrees magnetic), computed airspeed, CAS (knots), pressure altitude, PALT (feet), longitudinal acceleration, GX (g-units), pitch (degrees), roll (degrees), normal acceleration GZ (g-units) and error scores (six values for the six main variables (in the order CAS, Z_p, g_x, θ, ϕ, g_z). In addition, values are computed of ground speed change (GSC), air speed change (ASC) and headwind component change (HWCC = ASC - GSC) over the previous one-second period. (Data-point n-1 to data point n). Change in ground speed is estimated as follows:-

$$GSC_n = (\Delta V_g)_n = \left(\frac{\partial V_g}{\partial t}\right)_{n-\frac{1}{2}} \Delta t$$

$$= 19.06\,\Delta t\,(\bar{g}_x \cos\bar{\theta} - \bar{g}_z \sin\bar{\theta}\cos\bar{\phi}) \text{ knots}$$

where $\Delta t = 1$ second

In the above equation the overbar denotes one-second filtered values, the filters being centred at $n-\frac{1}{2}$ and covering the period n-1 to n. (See Figure A2).

The next stage of quality control consisted of visual examination of graphic data, one for each flight, of the estimated headwind component (with arbitrary origin) versus flight time (and pressure altitude) for the lowest 2000 feet of

approach or climb-out. Examples of these graphic plots is shown in Figures A4 and A5. For landings the "flight time" is the time in seconds before touch-down time, while for take-offs it is the time since lift-off. Each graph is labelled with basic information as follows:-

a. Whether a landing (LAND) or a take-off (T/OFF)

b. Aircraft's heading (degrees magnetic) at touchdown or lift off (top line, last item).

c. Date/time/data-set reference number of flight (second line).

d. Maximum and minimum "404" ramp-pairs encountered (plotted on profile as X).

e. Maximum and minimum "808" ramp-pairs encountered (plotted on profile as ⊡).

f. Surface wind (10-min average) } at last clock hour

g. Gradient wind } (values logged by Met Office staff)

h. Indication of whether a Windshear warning was in force at the time. If value = 0 no warning was in force; if value $\geq$ 0 a warning was in force, the value indicating which rule was satisfied - 1 (strong wind rule), 2, 3, 4 (vertical wind shear rules), 5 (thunderstorm or cumulonimbus), 6 (front), 7 (low-level jet), 8 (aircraft report during previous hour), 9 (warning issued in error).

Following visual examination of these headwind profiles:

(i) it was decided to eliminate flights with rate of change of headwind component (averaged over lowest 2000 feet) in excess of 1.5 kn s^{-1}. Where these excessive rates of change occurred, they were largely constant over the period of the approach or climb-out and were almost certainly attributable to unacceptably large errors in the datum value for g_x. Four flights were eliminated from the winter batch for this reason.

(ii) Seventeen flights from the winter batch and ten from the summer batch were eliminated because some aspect of the headwind profile appeared unrealistic.

Further substantial eliminations from the flight-recorder data at this stage included:-

a) Winter batch

24 Glasgow flights } apparently included with original
24 flights from unknown airfields } Heathrow tapes in error

60 flights outside period of main study (9 Jan - 31 Mar 1977).

b) Summer batch

3 flights for unknown airfields

9 duplicated flights

30 flights outside period of main study (1 Jul - 25 Aug 1977).

Appendix 3. Description of data-set created by Windshear Analysis Program

For each take-off or landing the following items are extracted or computed and stored in a new data-set - the Flight Summary data-set.

Record 1 - Basic Flight information.

Aircraft type	= 2 for Trident		
Date	dd mmyy		
Time	zzzz (GMT)		
ORIDE	= T for take-off,	= F for landing	
HWC	Total change in headwind component for this flight		(knots)
TFLT	Duration of data for this flight		(seconds)
Rate of change of headwind component averaged over TFLT* (HWC/TFLT)			(knots s^{-1})
HDG1	Heading at 1st second	(at t = 1)	(deg.mag)
HDG2	Heading at last second	(at t = TFLT)	(deg.mag)
PALT1	Pressure altitude at t = 1		(feet)
PALT2	Pressure altitude at t = TFLT		(feet)

Records 2-7 - Computed windshears for 404, 424, 444, 808, 848, 888 ramp pairs respectively (maximum, minimum values encountered)

Each of these six records contains:-

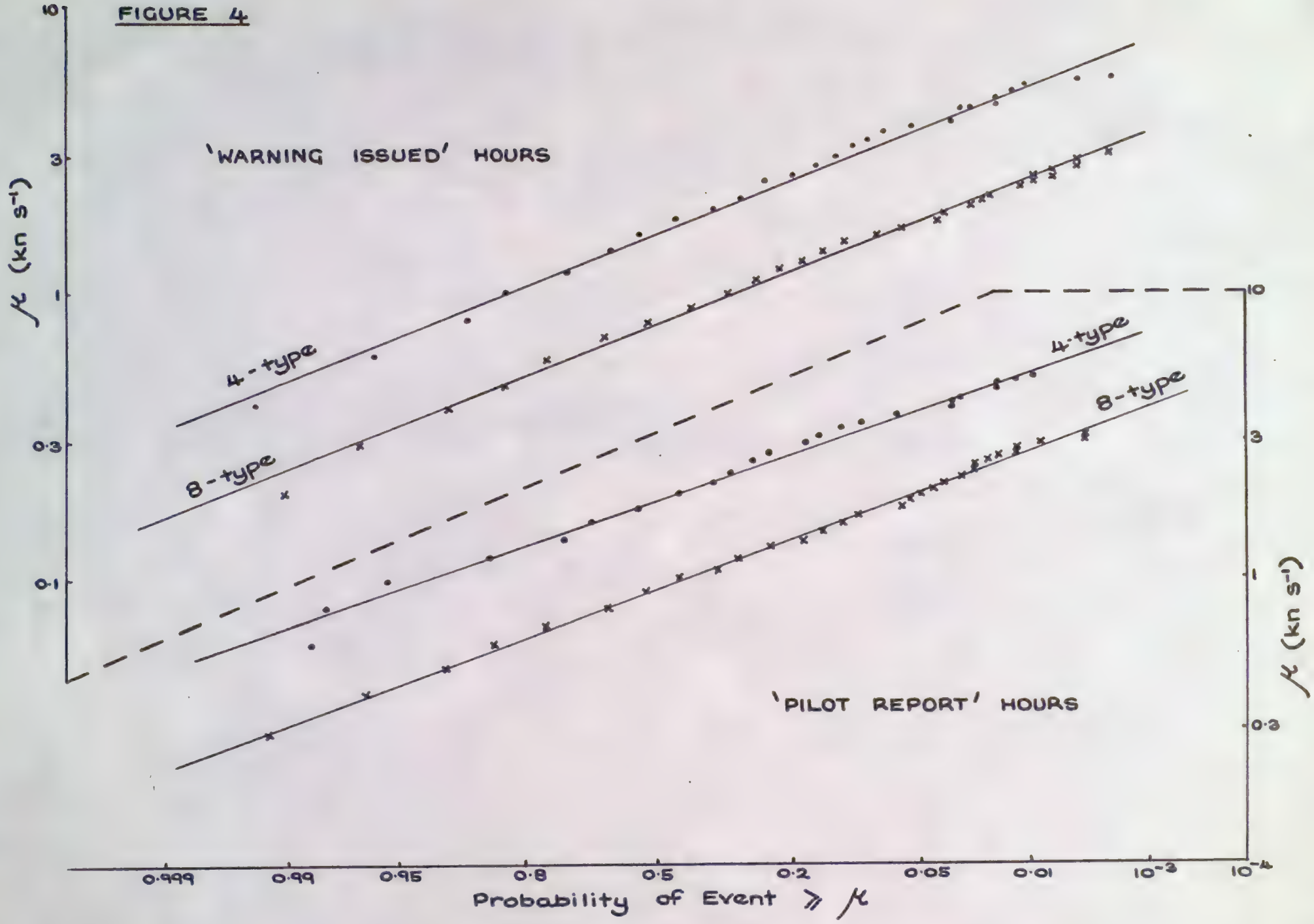
data on UID_{max}
- (Data point (second count) associated with maximum ramp pair, UID_{max}
- (Maximum TT_sT ramp pair value encountered on this flight (knots s^{-1})
- (Pressure altitude associated with UID_{max} (feet)
- (Heading value associated with UID_{max} (deg.mag)
- (Error scores (for CAS, PALT, $\overline{g_x}$, $\overline{\theta}$, $\overline{\phi}$, $\overline{g_z}$) associated with UID_{max}

Similarly for UID_{min}

Record 8 - Meteorological variables, aircraft movements, numbers of (written) pilots' reports of Windshear, for current hour (see Appendix 1C for full list of variables in this record).

* If HWC/TFLT $\geq$ 1.5 kn s^{-1}, only Record 1 was written.

FIGURE 4


'WARNING ISSUED' HOURS
'PILOT REPORT' HOURS
4-type
8-type
4-type
8-type
κ (kn s⁻¹)
κ (kn s⁻¹)
10
3
1
0·3
0·1
10
3
1
0·3
0·999
0·99
0·95
0·8
0·5
0·2
0·05
0·01
10⁻³
10⁻⁴
Probability of Event ⩾ κ

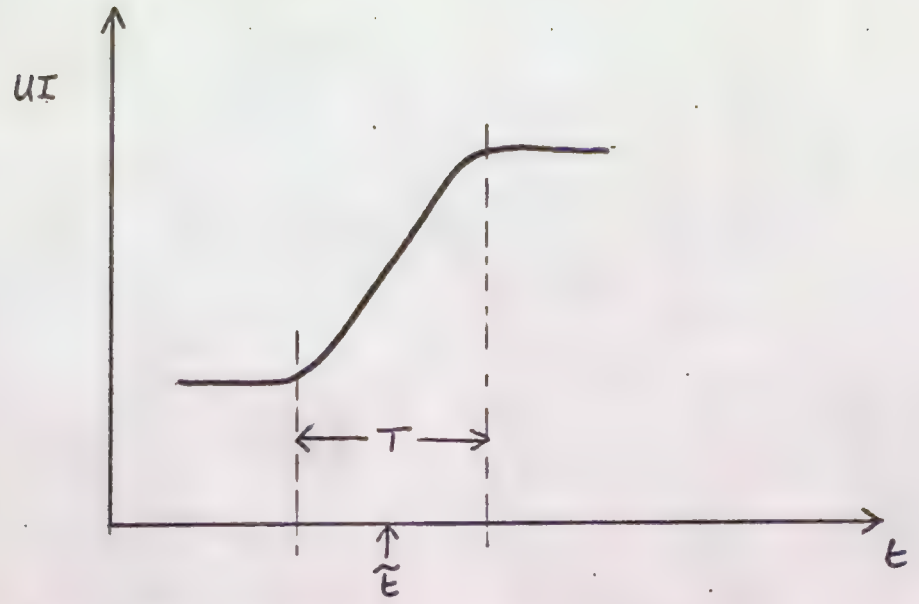


Fig. ~~5~~ 1. Idealised headwind component profile for NR = 1 (single ramp)
(Windshear Analysis Program)

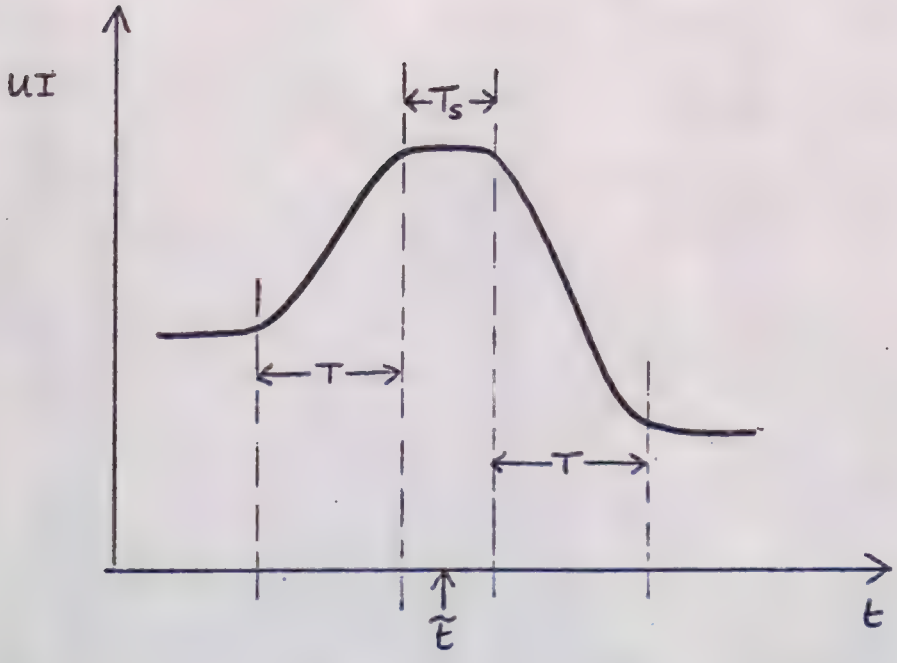
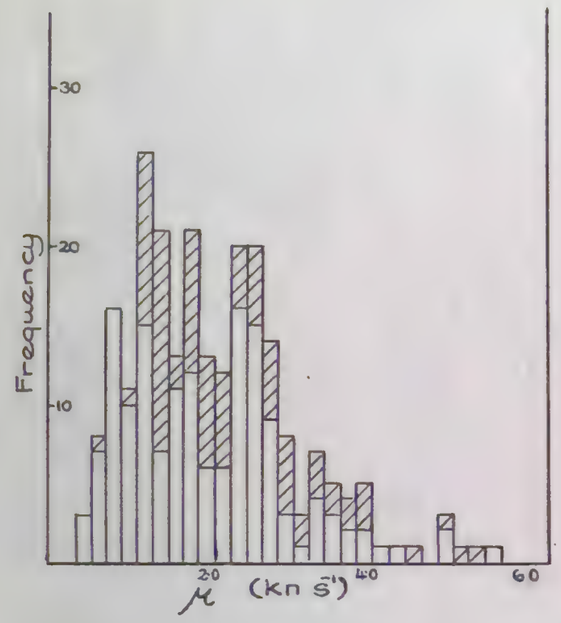
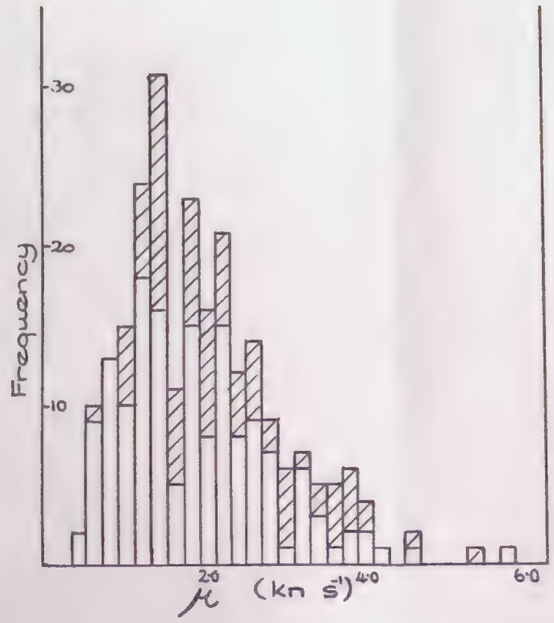


Fig. 2. Idealised headwind component profile for NR = 2 (double ramp)
(Windshear Analysis Program)

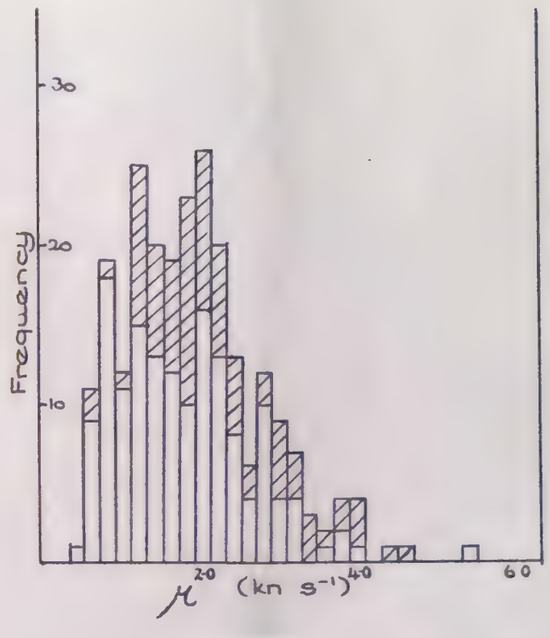
404



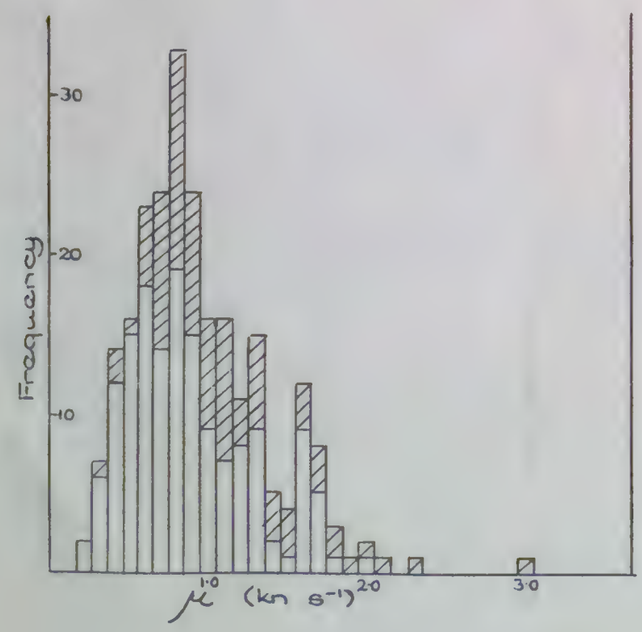
424



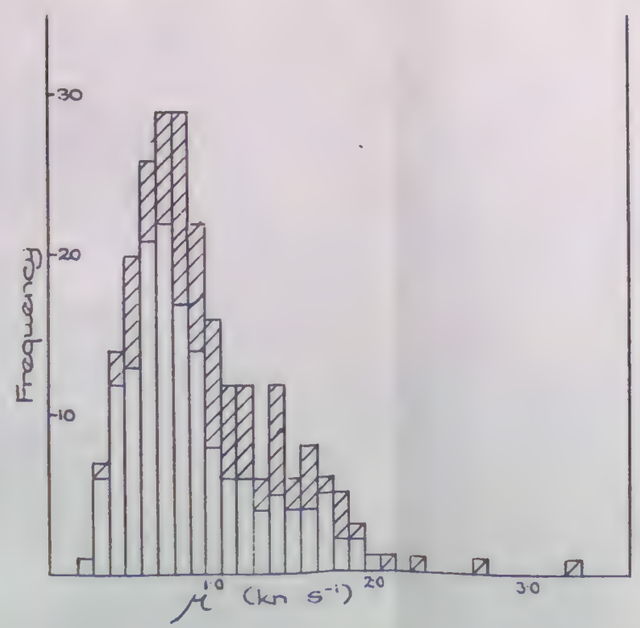
444



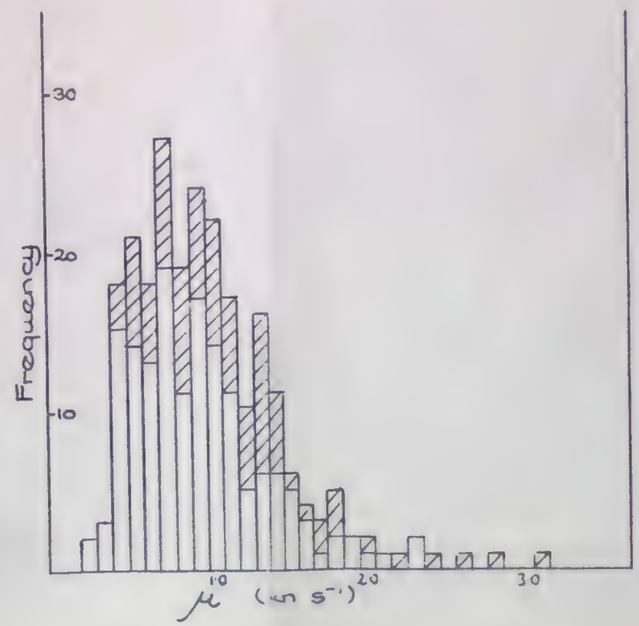
808



848



888



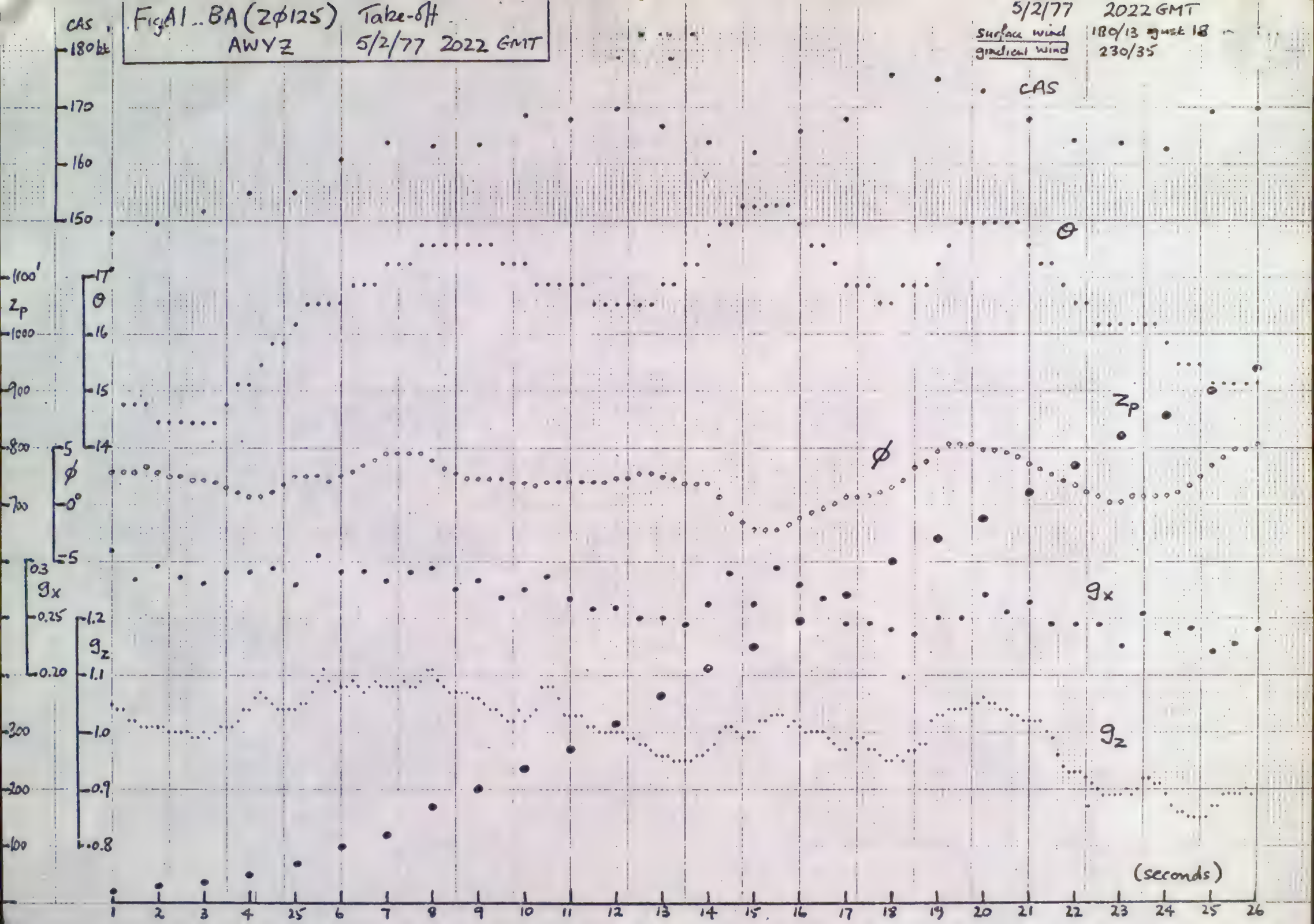


Fig A1..8A (2φ125) Take-off
AWYZ
5/2/77 2022 GMT
5/2/77 2022 GMT
surface wind 180/13 gust 18
gradient wind 230/35
CAS
180 kt
170
160
150
θ
17°
16
15
14
Zp
1100'
1000
900
800
700
φ
5
0°
-5
gx
0.3
0.25
0.20
gz
1.2
1.1
1.0
0.9
0.8
200
100
(seconds)
1 2 3 4 25 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

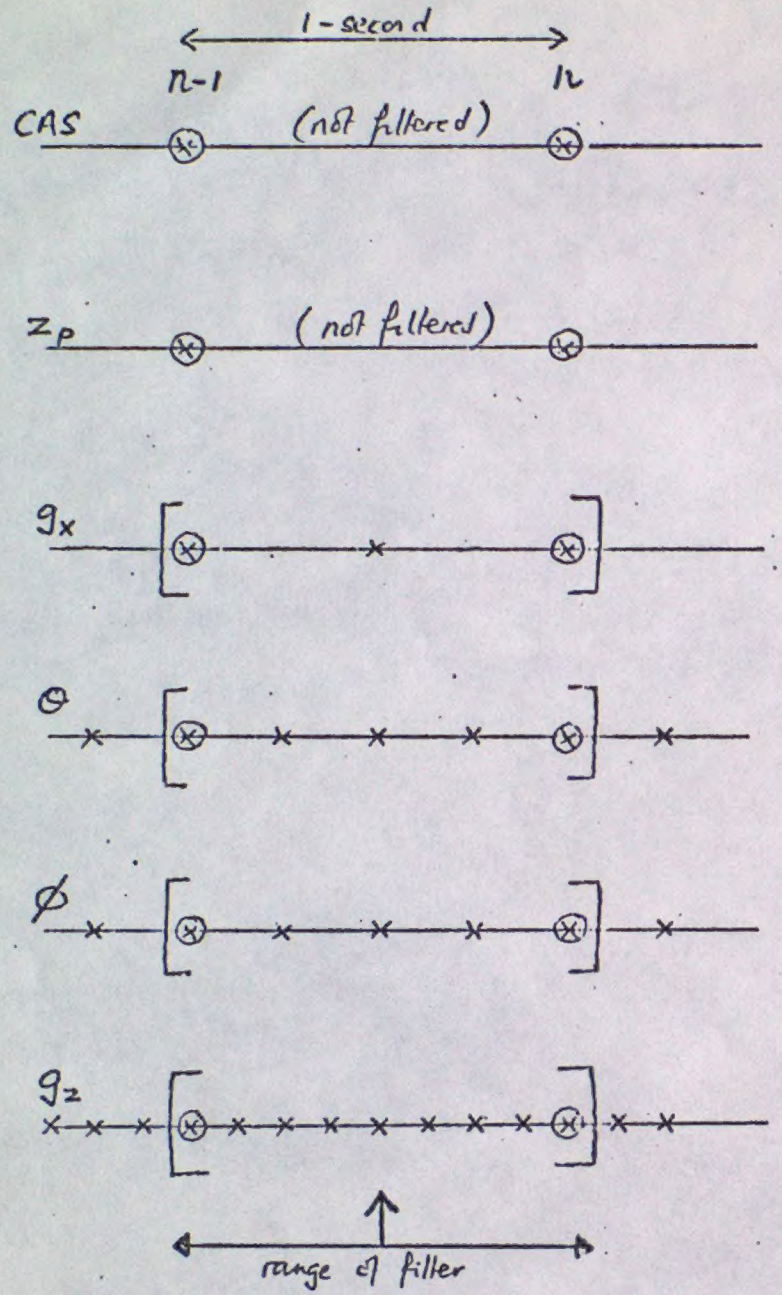


Fig A2. Calculation of headwind component changes over 1-second intervals after preliminary filtering

Change in airspeed from second n-1 to second n given by:

$$(\Delta CAS)_n = (CAS)_n - (CAS)_{n-1} \qquad \text{(knots)}$$

CAS not filtered

z_p not filtered

g_x, θ, ϕ, g_z filtered using

(1 5 1)	3-pt triangular
(1 4 6 4 1)	5-pt binomial
(1 4 6 4 1)	5-pt binomial
(1 2 3 4 5 4 3 2 1)	9-pt triangular

filter

The values covered by the various filters are enclosed by square brackets in the diagram opposite (filters centred at $n-\frac{1}{2}$)

Estimate of change in groundspeed from second n-1 to second n :-

$$(\Delta V_g)_n = (V_g)_n - (V_g)_{n-1}$$
$$= (\bar{g}_x \cos\bar{\theta} - \bar{g}_z \sin\bar{\theta}\cos\bar{\phi}) \times 19.06 \qquad \text{(knots)}$$

Estimate of change in headwind component from second n-1 to second n is then given by:

$$(\Delta u)_n = (\Delta CAS)_n - (\Delta V_g)_n \qquad \text{(knots)}$$

Fig A3 Sample of Quality controlled and filtered aircraft data

TRIDENT (HEATHROW) FLIGHT DATA AT 1-SEC INTERVALS (FILTERED OVER 1-SEC PERIODS) DSN=M09. 73.BAEDDENT

DATE	GMT	SEC	HEADING	CAS	P.ALT	GX	PITCH	ROLL	GZ	GSC	ASC	HWCC	ERROR SCORES
2 13 1 1977	1048.00	77.00	106.52	177.46	2115.00	0.018	0.813	-0.308	1.009	0.074	0.0	0.0	0 0 0 0 0 0
2 13 1 1977	1048.00	78.00	105.82	176.76	2105.00	0.022	0.703	0.352	1.005	0.175	-0.703	-0.878	0 0 0 0 0 0
2 13 1 1977	1048.00	79.00	105.82	176.76	2090.00	0.022	0.703	0.110	1.002	0.176	0.0	-0.176	0 0 0 0 0 0
2 13 1 1977	1047.00	80.00	105.47	177.46	2075.00	0.024	0.791	0.352	1.010	0.167	0.703	0.516	0 0 0 0 0 0
2 13 1 1977	1047.00	81.00	105.12	178.52	2055.00	0.018	0.703	0.044	1.007	0.100	1.055	0.954	0 0 0 0 0 0
2 13 1 1977	1048.00	82.00	104.77	178.16	2040.00	0.018	0.703	-0.022	1.006	0.101	-0.352	-0.452	0 0 0 0 0 0
2 13 1 1977	1048.00	83.00	104.41	178.16	2025.00	0.021	0.593	-0.352	1.013	0.200	0.0	-0.200	0 0 0 0 0 0
2 13 1 1977	1048.00	84.00	104.77	178.16	1995.00	0.018	0.374	-0.681	0.998	0.223	0.0	-0.223	0 0 0 0 0 0
2 13 1 1977	1048.00	85.00	105.12	177.81	1980.00	0.021	0.703	-0.110	1.016	0.162	-0.352	-0.514	0 0 0 0 0 0
2 13 1 1977	1047.00	86.00	105.12	179.22	1960.00	0.019	0.703	0.571	1.018	0.130	1.406	1.276	0 0 0 0 0 0
2 13 1 1977	1047.00	87.00	105.12	178.16	1940.00	0.019	0.703	0.132	1.019	0.119	-1.055	-1.174	0 0 0 0 0 0
2 13 1 1977	1047.00	88.00	105.12	179.22	1920.00	0.015	0.703	0.593	0.994	0.061	1.055	0.994	0 0 0 0 0 0
2 13 1 1977	1048.00	89.00	105.12	179.57	1895.00	0.029	0.703	0.571	1.011	0.312	0.352	0.039	0 0 0 0 0 0
2 13 1 1977	1048.00	90.00	104.77	178.87	1880.00	0.019	0.703	0.242	1.038	0.125	-0.703	-0.828	0 0 0 0 0 0
2 13 1 1977	1048.00	91.00	104.77	177.46	1855.00	0.010	0.703	0.110	1.027	-0.053	-1.406	-1.353	0 0 0 0 0 0
2 13 1 1977	1048.00	92.00	104.77	176.76	1845.00	-0.005	0.703	0.110	0.975	-0.318	-0.703	-0.386	0 0 0 0 0 0
2 13 1 1977	1047.00	93.00	105.12	176.41	1845.00	0.003	0.703	-0.022	1.014	-0.178	-0.352	-0.174	0 0 0 0 0 0
2 13 1 1977	1047.00	94.00	105.12	175.70	1825.00	-0.006	1.033	0.154	0.988	-0.461	-0.703	-0.242	0 0 0 0 0 0
2 13 1 1977	1047.00	95.00	105.47	176.76	1800.00	0.001	1.055	0.571	1.004	-0.325	1.055	1.380	0 0 0 0 0 0
2 13 1 1977	1048.00	96.00	105.12	175.35	1785.00	0.012	1.384	0.703	1.050	-0.254	-1.406	-1.152	0 0 0 0 0 0
2 13 1 1977	1048.00	97.00	104.06	173.24	1755.00	0.015	1.165	1.274	1.038	-0.109	-2.109	-2.001	0 0 0 0 0 0
2 13 1 1977	1048.00	98.00	104.06	175.00	1740.00	0.015	1.165	0.154	0.979	-0.097	1.758	1.654	0 0 0 0 0 0
2 13 1 1977	1048.00	99.00	104.06	176.05	1725.00	0.018	1.406	0.417	1.012	-0.138	1.055	1.192	0 0 0 0 0 0
2 13 1 1977	1048.00	100.00	104.06	175.00	1705.00	0.016	1.476	0.483	1.023	-0.175	-1.055	-0.880	0 0 0 0 0 0
2 13 1 1977	1047.00	101.00	104.06	174.30	1685.00	0.025	1.428	0.945	1.011	-0.096	-0.703	-0.697	0 0 0 0 0 0
2 13 1 1977	1047.00	102.00	103.71	175.00	1675.00	0.032	1.758	0.681	1.022	0.004	0.703	0.699	0 0 0 0 0 0
2 13 1 1977	1048.00	103.00	103.71	174.30	1660.00	0.032	1.758	0.483	1.036	0.006	-0.703	-0.709	0 0 0 0 0 0
2 13 1 1977	1048.00	104.00	104.41	173.59	1640.00	0.024	1.758	0.725	1.003	-0.123	-0.703	-0.580	0 0 0 0 0 0
2 13 1 1977	1048.00	105.00	104.41	173.24	1635.00	0.033	2.087	0.857	1.023	-0.088	-0.352	-0.264	0 0 0 0 0 0
2 13 1 1977	1048.00	106.00	104.41	172.54	1620.00	0.039	1.890	0.989	1.027	0.094	-0.703	-0.796	0 0 0 0 0 0
2 13 1 1977	1048.00	107.00	104.41	172.89	1600.00	0.041	2.131	1.296	1.025	0.045	0.352	0.307	0 0 0 0 0 0
2 13 1 1977	1047.00	108.00	104.77	172.89	1590.00	0.041	2.483	1.055	1.040	-0.076	0.0	0.076	0 0 0 0 0 0
2 13 1 1977	1048.00	109.00	104.77	171.84	1575.00	0.044	2.681	1.296	1.033	-0.086	-1.055	-0.969	0 0 0 0 0 0
2 13 1 1977	1047.00	110.00	104.77	171.13	1560.00	0.044	2.483	1.626	1.027	-0.013	-0.703	-0.690	0 0 0 0 0 0
2 13 1 1977	1047.00	111.00	104.77	169.73	1540.00	0.038	2.483	1.077	0.963	-0.066	-1.406	-1.340	0 0 0 0 0 0
2 13 1 1977	1048.00	112.00	104.41	168.67	1525.00	0.043	2.483	1.143	0.996	-0.008	-1.055	-1.046	0 0 0 0 0 0
2 13 1 1977	1048.00	113.00	104.41	169.02	1515.00	0.059	2.461	1.033	1.044	0.267	0.352	0.084	0 0 0 0 0 0
2 13 1 1977	1048.00	114.00	104.77	167.62	1500.00	0.055	2.900	0.154	1.021	0.063	-1.406	-1.469	0 0 0 0 0 0
2 13 1 1977	1048.00	115.00	105.82	166.56	1485.00	0.060	2.944	0.264	1.018	0.146	-1.055	-1.201	0 0 0 0 0 0
2 13 1 1977	1048.00	116.00	105.82	165.16	1480.00	0.052	3.296	1.165	0.988	-0.088	-1.406	-1.318	0 0 0 0 0 0
2 13 1 1977	1048.00	117.00	104.77	166.32	1470.00	0.064	3.252	2.659	1.046	0.087	3.164	3.078	0 0 0 0 0 0
2 13 1 1977	1048.00	118.00	104.06	166.21	1460.00	0.060	3.252	1.406	1.043	0.015	-2.109	-2.125	0 0 0 0 0 0
2 13 1 1977	1048.00	119.00	104.41	167.97	1450.00	0.058	3.164	0.022	1.017	0.041	1.758	1.717	0 0 0 0 0 0
2 13 1 1977	1048.00	120.00	104.41	166.91	1440.00	0.047	2.922	0.110	1.041	-0.113	-1.055	-0.942	0 0 0 0 0 0
2 13 1 1977	1048.00	121.00	104.06	165.16	1430.00	0.035	2.725	0.242	1.019	-0.258	-1.758	-1.499	0 0 0 0 0 0
2 13 1 1977	1048.00	122.00	103.71	165.86	1425.00	0.026	2.483	-0.154	1.013	-0.342	0.703	1.045	0 0 0 0 0 0
2 13 1 1977	1048.00	123.00	104.06	164.10	1425.00	0.020	2.329	-0.961	1.046	-0.432	-1.758	-1.326	0 0 0 0 0 0
2 13 1 1977	1048.00	124.00	103.71	161.29	1415.00	0.006	1.516	-0.022	0.994	-0.378	-2.813	-2.434	0 0 0 0 0 0
2 13 1 1977	1048.00	125.00	104.06	161.99	1405.00	-0.003	1.143	-0.374	0.988	-0.433	0.703	1.136	0 0 0 0 0 0
2 13 1 1977	1048.00	126.00	104.41	160.59	1390.00	-0.012	0.681	-0.022	1.003	-0.455	-1.406	-0.951	0 0 0 0 0 0
2 13 1 1977	1047.00	127.00	104.77	161.64	1375.00	-0.022	0.242	0.615	0.974	-0.498	1.055	1.552	0 0 0 0 0 0
2 13 1 1977	1048.00	128.00	104.41	159.18	1360.00	-0.037	-0.330	1.318	0.962	-0.590	-2.461	-1.871	0 0 0 0 0 0
2 13 1 1977	1048.00	129.00	104.06	156.02	1340.00	-0.044	-0.791	1.934	0.954	-0.594	-3.164	-2.570	0 0 0 0 0 0
2 13 1 1977	1048.00	130.00	103.36	152.15	1325.00	-0.039	-1.296	0.747	0.964	-0.322	-3.867	-3.545	0 0 0 0 0 0
2 13 1 1977	1048.00	131.00	103.36	154.26	1310.00	-0.024	-1.406	0.857	0.988	0.001	2.109	2.109	0 0 0 0 0 0

FIGURE A4

BA TRIDENT LAND HTRW 226
25/1/1977 1910GMT FLNO 76

RAMP PAIRS (KN/S) 404 × 4.1.-5.0 808 □ 2.2.-1.8

MET WINDS SURF 210/26 GRAD 230/70 WARNING 8

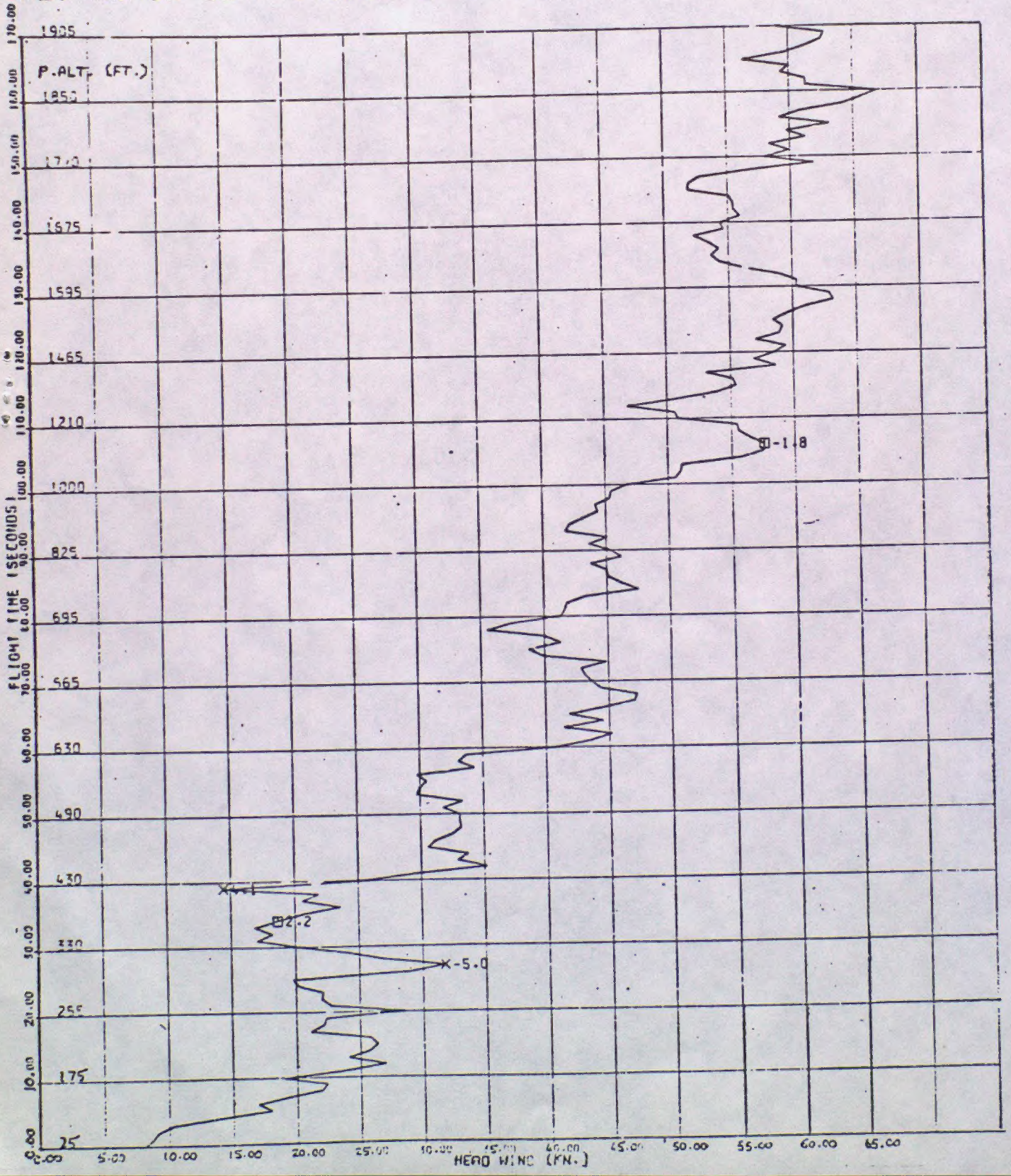
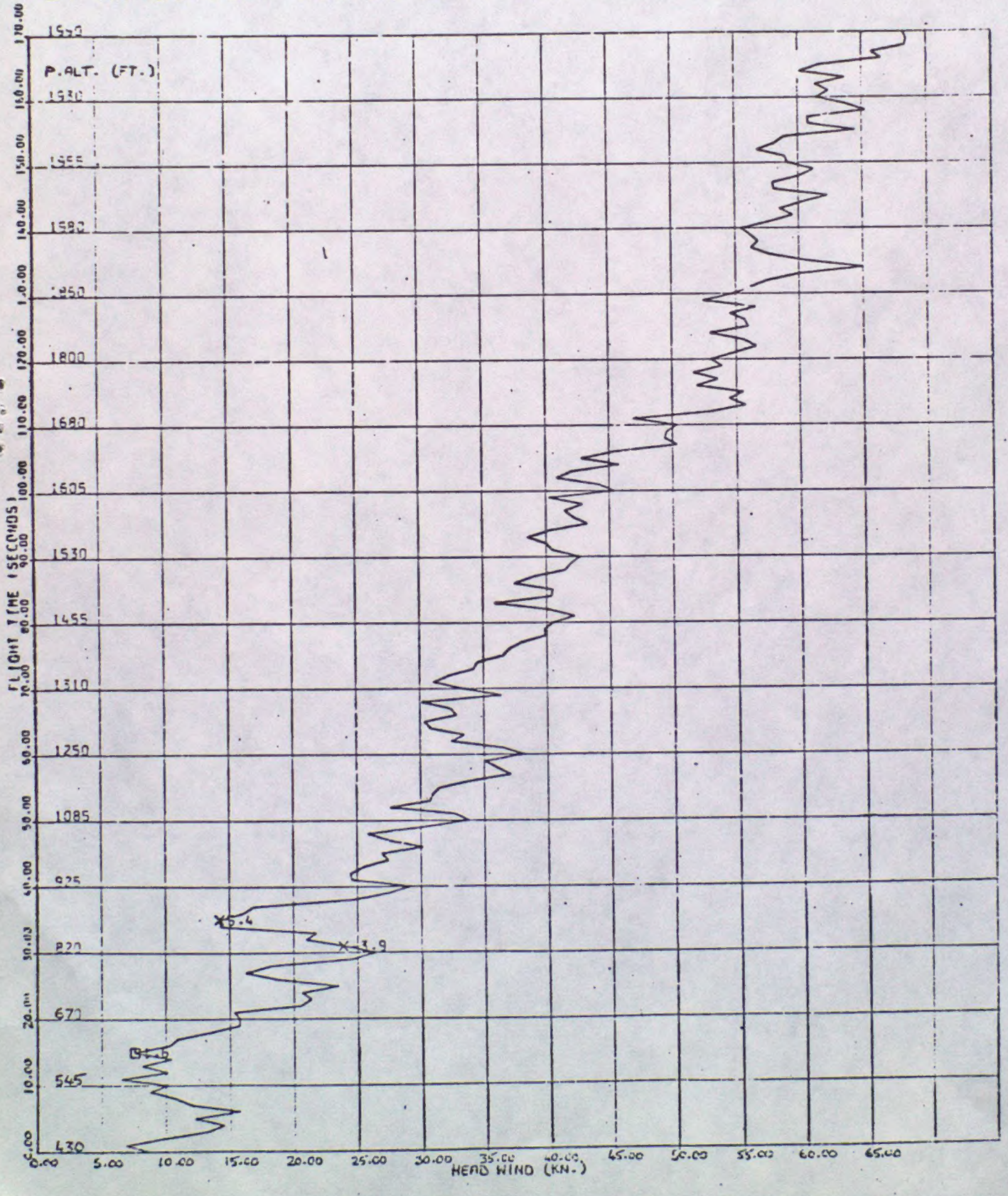


FIGURE A5

BA TRIDENT LAND HTRW 228
25/1/1977 1955GMT FLNO 77

RAMP PAIRS (KN/S) 404 × 5.4.-3.9 808 □ 1.6.-1.6

MET WINDS SURF 210/26 GRAD 230/70 WARNING 8